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The objective of this research in magnetospheric physics was to advance understanding of the interaction of ring current ions with magnetospheric hydromagnetic waves. The goal was to examine the excitation of westward propagatirig hydromagnetic waves by drift-bounce resonance with 100 to 200 MeV ring current protons using a 3D MHD code in dipole geometry which incorporates the ring current ions via a gyrokinetic treatment. This was the first self-consistent study of this phenomenon. An extension of the ring current particle trajectory tracing code, developed with Air Force support, was used to study the rapid formation of new electron and proton radiation belts. The model has been highly successful at explaining the observed acceleration of electrons and protons by tens of MeV in less than a drift period.

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Final Progress Report on

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Self-Consistent Effects of Magnetospheric Hydromagnetic Waves on Ring Current Ions

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(a) Objectives

The objective of this research in magnetospheric physics is to advance understanding of the interaction of ring current ions with magnetospheric hydromagnetic waves. The goal is to examine the excitation of westward propagating hydromagnetic waves by drift-bounce resonance with 100–200 keV ring current protons using a 3D MHD code in dipole geometry which incorporates the ring current ions via a gyrokinetic treatment. This will be the first self-consistent study of this phenomenon. An extension of the ring current particle trajectory tracing code, developed with Air Force support, is being used to study the rapid formation of new electron and proton radiation belts, as observed on March 24, 1991. The model has been highly successful at explaining the observed acceleration of electrons and protons by tens of MeV in less than a drift period, and the focus is now shifting to study of the ULF oscillations which persisted during the hours to days of the ensuing geomagnetic storm.

(b) Accomplishments

Work this year has focused on (i) exploring the basic properties of two types of global ULF waves, the global poloidal mode and the inner magnetospheric cavity mode, using a 2D and 3D code which solves the ideal MHD equations in dipole geometry [*Denton,* 1997]; (ii) development of a set of gyrokinetic equations and their numerical implementation, adding a ring current source to the MHD equations [*Belova et al.,* 1997]; (iii) incorporation of finite ion pressure into the MHD equations, and their numerical implementation in box geometry [*Marchenko et al.,* 1996]; (iv) simulation of proton radiation belt formation during geomagnetic storm sudden commencements and loss during main phase [*Hudson et al.,* 1996a, b; 1997a, b].

(i) Ideal MHD Code Poloidal Mode and Cavity Mode Study [*Denton,* 1997]

One key question relating to the poloidal mode, and the one on which we have concentrated, is what determines the radial structure of the mode. For a monotonically decreasing mode frequency with respect to L shell, ideal MHD predicts that the mode structure will be singular as we [*Ding et al.,* 1995] and others have shown. There are several possible determining

factors for mode width including ionospheric resistivity and finite Larmor radius effects. Another possible explanation for mode width based entirely on ideal MHD is the mechanism of *Vetoulis and Chen* [1994; 1996]. They propose that a dip in poloidal mode frequency due to a pressure gradient could lead to a localized mode. We have recently examined this mechanism [*Denton and Vetoulis,* 1997] and found that the mechanism does work, though there are some questions as to whether conditions favorable to such a frequency dip can occur. In the process of examining this mechanism, we demonstrated the compressible nature of the poloidal mode [*Denton,* 1997]. We plan further to investigate the effect of finite Larmor radius on the mode using finite Larmor radius MHD equations which we have derived [*Marchenko et al.,* 1996].

In our cavity mode study, we seek to gain a quantitative understanding of the cavity mode structure in the inner magnetosphere, including the frequencies one should expect to see in ground and satellite magnetometer data. Until now, most of the development of the cavity mode theory has focused on the outer magnetospheric cavity; however, as hypothesized by *Samson and Harrold* [1992], the outer magnetospheric geometry may be better described as a waveguide, in which waves travel antisunward through the tail. Unlike the outer cavity, the plasmasphere is entirely enclosed by the plasmapause-ionosphere surface, and so should form a good resonant cavity for ULF waves. Computations in a cartesian geometry indicate that this assumption is correct. We have written a dynamic MHD "box" simulation which not only reproduces aspects of the work of *Inhester* [1987] and *Zhu and Kivelson* [1988; 1989], but which suggests that resonant modes can occupy the inner magnetosphere. Outer cavity modes can excite and couple with resonances in the plasmasphere, and at times the plasmasphere modes are dominant; i. e. the wave disturbances are localized to the plasmasphere, with little activity in the outer magnetosphere. With this work as motivation, we have developed a dipole code for the simulation of the plasmasphere. (Dipole geometry should be sufficient for the low L shell plasmasphere.) One of the key features of this code is a spherical shell ionosphere boundary, so that more realistic FLR frequencies can be determined. Initial results suggest that the cavity modes in the plasmasphere will qualitatively resemble those found in previous studies of the outer magnetospheric cavity modes, but with much higher

frequencies.

(ii) Hybrid MHD Code Ring Current Incorporation [*Belova et al.,* 1997]

Both a 2D and 3D version of a hybrid gyrokinetic-MHD code have been developed to couple ring current pressure into the MHD equations, and to self-consistently push the ions with the MHD fields [*Belova et al.,* 1995]. We have Lorentz-force and drift-kinetic versions of the hybrid code with which we can compare runs. The code has flexible options for boundary conditions and uses generalized orthogonal coordinates, so it will not be difficult to change from box-periodic to an inhomogeneous system with curvilinear coordinates. The major coding effort is therefore complete, and we expect to replace the continuous prescribed internal perturbation in (i) with the ring current free energy source. This is Elena Belova's Ph. D. thesis project.

(iii) Nonlinear Kinetic Alfvén Waves with Finite Ion Larmor Radius [*Marchenko et al.,* 1996]

The effects of finite ion Larmor radius in the description of two types of nonlinear dispersive Alfvén waves propagating in the magnetosphere, the nonlinear kinetic and inertial Alfvén waves, are usually disregarded. However, under magnetospheric conditions, ion temperature cannot be considered negligible. In order to revise the theory, we have derived a reduced low frequency description that includes the effects of finite ion temperature as well as electron inertia and electron pressure in nonlinear Alfvén wave dynamics [*Marchenko et al.,* 1996]. The obtained set of equations contains all the physical terms necessary to describe kinetic Alfvén waves and gives a correct dispersion relation in the linear limit. In addition, a way to incorporate finite ion Larmor radius corrections into the MHD code as a fluid pressure correction has been obtained and coded in box geometry. This will eliminate grid scale effects on the radial mode structure found by *Ding et al.* [1995] and will incorporate the dispersive properties of "kinetic" Alfvén waves into the code.

(iv) Radiation Belt Results [*Hudson et al.,* 1996a, b; 1997a, b]

We developed a model for the formation of the new radiation belts following the March 24,

1991 SSC. Results have now been published for the electrons [*Li et al.,* 1996], and the protons [*Hudson et al.,* 1996a, b]. The March 1991 storm was a remarkable event, and we are very pleased with the explanation of the rapid acceleration and formation of the belts obtained from our relatively simple model involving the induction electric field from the SSC compression. Simulation of the SSC has illuminated the rapid formation of new radiation belts on the particle drift time scale. The simulations reproduce several important features of the new proton belt which resulted from the March 24, 1991 SSC. Progress has been achieved on modifying the code to run on a Cray T3D/T3E parallel computer in order to examine the effect of the prescribed pulse on non-equatorially mirroring particles. The parallel code, which is being developed by graduate student Scot Elkington, is now operational. Several smaller MeV proton events with comparable particle morphology, but less radial transport and energization, were observed during the July 1990 - October 1991 period. Fields are incorporated from John Lyon's global MHD simulation of the smaller events. Graduate student Jerry Goldstein is assisting with the global MHD simulations. An SSC accompanied by solar protons produces a trapped population which remains on closed drift orbits until ring current buildup disrupts trapping, either by violation of the adiabatic trapping criterion or generation of waves whose frequency is comparable to periodic particle motion. Our results have shown that new radiation belts formed around L=4 by SSC injection are short-lived compared to the March 24, 1991, storm, wherein solar protons were transported radially inward to L=2.5, with greater energization corresponding to first adiabatic invariant conservation than for the weaker events.

(v) Data Survey [*Lessard and Hudson,* 1996]

Graduate student Marc Lessard is completing a survey of the Ampte/IRM data set, made available to us on CD-ROM, for the statistical occurence properties of Pc 5 pulsations, namely that class of ULF oscillations which are excited by the ring current drift bounce resonance interaction. Results were presented at a Spring AGU Meeting [*Lessard et al.,* 1995], now a preprint, and indicate peak occurrence on the dayside near dawn and dusk, with a secondary maximum on the nightside. He is also analysing observations of field line resonances generated by cavity mode pulsations [*Lessard and Hudson,* 1996]. An attempt is

being undertaken to understand an apparent discrepancy between ground-based and satellite measurements of these resonances.

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(c) Publications

See **References**, excluding *Inhester* [1987], *Samson and Harrold* [1992], *Vetoulis and Chen* [1994; 1996], and *Zhu and Kivelson* [1988; 1989].

(d) Personnel

Drs. Mary K. Hudson, John G. Lyon, Richard E. Denton, and Victor A. Marchenko; Elena Belova, Scot Elkington, Jerry Goldstein and Marc Lessard, Dartmouth graduate students.

(e) Interactions

Dr. Mary Hudson presented results from incorporation of fields from John Lyon's global MHD simulation of the March 24, 1991, SSC, as well as of the smaller events, into test particle modelling of the formation of new radiation belts at a number of conferences and workshops, including JPL Chapman Conference on Magnetic Storms in February in Pasadena, CA, AGU Meetings, COSPAR Conference in July in Birmingham, England, and Huntsville ISTP Workshop in September in Guntersville, AL. In preparation for these meetings, Hudson discussed CRRES data for the proton events with Dr. Sue Gussenhoven of Phillips Laboratory and Dr. Bernie Blake of The Aerospace Corporation, as well as Drs. John Wygant (University of Minnessota) and Howard Singer (NOAA) who have analyzed the field data from CRRES. The Chapman and COSPAR Conferences were particularly highly informative follow-ups to the Taos Workshop of 1994, bringing together more international participation.

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